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## AUTO CORRECTING TEMPERATURE TRANSMITTER WITH RESISTANCE BASED SENSOR

### BACKGROUND OF THE INVENTION

The present invention relates to transmitters  
5 of the type used in the process control industry. More specifically, the invention relates to diagnostics for process control transmitters which include a resistance based temperature sensor.

Process control transmitters are used to  
10 monitor process variables in industrial processes. For example, a transmitter might monitor temperature and transmit such information back to a control room. Furthermore, some transmitters are capable of performing the control function directly. In order to monitor a  
15 process variable, the transmitter must include a sensor, for example, an RTD which is a resistance based temperature sensor.

As the RTD sensor ages or is subjected to harsh environmental conditions, the accuracy of the  
20 sensor tends to degrade. It is possible to compensate for this degradation by periodically recalibrating the transmitter. Typically, this requires an operator to enter the field and perform a calibration process on-site on the transmitter. This is both inconvenient and  
25 time consuming for the operator. Further, it is difficult to determine the condition of a sensor, prior to its ultimate failure.

It is also necessary for the sensors to be periodically replaced as they age. However, it is  
30 difficult to determine precisely when a replacement is necessary. Therefore, sensors are typically replaced well before their failure or, in some cases, they may fail unexpectedly.

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SUMMARY OF THE INVENTION

A transmitter in a process control system includes a resistance-based sensor sensing a process variable and providing a sensor output. Self heating circuitry coupled to the sensor provides a self heating signal related to the sensor. Analog-to-digital conversion circuitry coupled to the sensor output provides a digitized sensor output, and transmitter output diagnostic correction circuitry provides an auto corrected output as a function of the self heating signal output or in another embodiment, the transmitter outputs a residual life estimate of the sensor as a function of the self heating index. A novel method of calculating the self heating index is also disclosed, for use in the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a process control system including a transmitter in accordance with the present invention.

Figure 2 is a block diagram of a transmitter of the present invention.

Figure 3 is a simplified block diagram of a transmitter in accordance with one embodiment of the invention.

Figure 4 is a simplified block diagram in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 is a diagram of process control system 2 including field mounted temperature transmitter 40 and a valve controller 12 coupled electrically to control room 4 over a two wire process control loops 6 and 14, respectively. Transmitter 40, mounted on a manifold and connected to the pipe via a manifold, monitors the temperature of process fluid in process

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18. However, the present invention applies to any resistance based process variable measurement such as a resistance based pressure measurement or a resistance based pH measurement. Transmitter 40  
5 transmits temperature information to control room 4 over loop 6 by controlling the current flowing through loop 6. For example, the current flowing through loop 6 may be controlled between 4 and 20 mA and properly calibrated to indicate temperature. Additionally or in  
10 the alternative, transmitter 40 may transmit digital information related to temperature over loop 6 to control room 4 such as in a HART® or an all digital protocol such as Fieldbus. Transmitter 40 includes circuitry described herein in more detail which provides  
15 advanced diagnostics related to temperature sensor operation.

One aspect of the present invention includes a recognition of a close correlation, in some cases linear relationship, of the SH index to the "alpha" and/or  $R_0$  of the sensor. As is known, alpha and/or  $R_0$  of a sensor is related to sensor calibration and therefore to sensor lifetime. Accordingly, if the SH index is measured, the lifetime of the sensor can be  
20 estimated. Furthermore, the sensor output can be corrected in real-time as a function of the amount of degradation (e.g., the difference between a preselected value of the SH index and the true current value of the SH index). This provides an autocorrection to the  
25 transmitter output.

30 One aspect of the invention includes a new technique for determining the self heating (SH) index of an RTD sensor. Typically, prior art self heating index measurement was performed by monitoring temperature change in the RTD due to an applied current. However,

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in a transmitter it is impractical to perform such a measurement due to power limitations and the necessity of a separate temperature measurement. The present invention includes defining the self heating index as the change in sensor resistance for a given change in the power input to the RTD sensor. This technique is preferable for a temperature transmitter because it does not require the RTD to be calibrated. Furthermore, the technique does not require the RTD to be removed from the process such that real-time data can be collected without the trouble and cost of interrupting the process. The self heating index can be calculated in a transmitter by applying two different input currents, for example, 5 mA and 15 mA. The resulting voltages across the RTD are measured and the resistance of the sensor is calculated at the two different currents using the equation  $R = V/I$ . The power applied to the RTD is determined at the two different currents as  $P = I \cdot V$ . The self heating index is calculated in accordance with equation 1:

$$SHI = \frac{R_1 - R_2}{P_1 - P_2} \quad \text{Eq. 1}$$

The invention can be practiced in any of a number of places in a process system control system. In particular, the present invention as realized in software and a microprocessor, can reside in a central controller or even a final control element 12 such as a valve, motor or switch as shown in Figure 1. Furthermore, modern digital protocols such as Fieldbus, Profibus and others allow for the software which practices the present invention to be communicated between elements in a process control system, and also

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provide for process variables to be sensed in one transmitter and then sent to the software.

Figure 2 is a simplified block diagram of a temperature transmitter 40 connected to RTD temperature sensor 10 in accordance with the present invention. Transmitter 40 includes terminal block 44, current source 45, multiplexer 46, differential amplifier 48, high accuracy A/D converter 50, microprocessor 52, clock circuit 54, memory 56 and input-output circuit 58.

Terminal block 44 includes terminals 1 through 5 for coupling to, for example, RTD temperature sensor 10. Sensor 10 can be either internal or external to transmitter 40. Sensor 10 includes RTD sensor element 61 having a resistance  $R_1$  which varies with changes in the ambient temperature. Leads 16 include four element leads 62, 64, 66 and 68. Lead 62 is connected between sensor element 61 and terminal 4, lead 64 is connected between sensor element 61 and terminal 3, lead 66 is connected between sensor element 61 and terminal 2, and lead 68 is connected between sensor element 61 and terminal 1.

Current source 45 is connected to terminal block 44 and supplies a measurement current  $I_s$  through terminal 4, sensor element 61, terminal 1, reference resistance  $R_{REF}$ , pull-down resistance  $R_2$  and ground terminal 72. Sensor element 61 develops a voltage drop across terminals 2 and 3 which is a function of the resistance  $R_1$  and thus the temperature of sensor element 61. Reference resistor  $R_{REF}$  is connected between terminal 1 and pull-down resistor  $R_2$ .

Multiplexer 46 is divided into two sections, an active multiplexer having an output connected to the non-inverting input of differential amplifier 48 and a reference multiplexer having an output connected to the

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inverting input of differential amplifier 48. Microprocessor 52 controls multiplexer 46 to multiplex appropriate sets of analog signals, including signals from terminals 1 through 3, to the non-inverting and  
5 inverting inputs of differential amplifier 48. Differential amplifier 48 has an output connected to A/D converter 50. In one embodiment, A/D converter 50 has an accuracy of 17 bits and a conversion rate of 14 samples/second. A/D converter 50 converts the voltage  
10 at the output of differential amplifier 48 into a digital value and provides that value to microprocessor 52 for analysis or for communication over process control loop 6 through input-output circuit 58.

Input-output circuit 58, in a preferred  
15 embodiment, includes a HART® communication section, a FIELDBUS communication section and a 4-20 mA analog loop section for analog or bi-directional digital  
20 communicating over loop 6 according to a selected protocol in a known manner. Other protocols can also be used, for example, a four-wire configuration may be employed in which power is received from a separate source. Loop 6 also provides power to the various components of transmitter 40 through input-output  
25 circuit 58. Preferably, transmitter 40 is wholly (completely) powered by the two-wire loop 6.

Memory 56 stores instructions and information for microprocessor 52, which operates at a speed determined by clock circuit 60. Clock circuit 60 includes a real time clock and a precision high speed  
30 clock, which are also used to sequence the operation of A/D converter 50. Microprocessor 52 performs several functions, including control of multiplexer 46 and A/D converter 50, control of communications over loop 6, temperature compensation, storage of transmitter

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configuration parameters and performing sensor diagnostics.

Microprocessor 52 employs the following equation to compute the temperature of RTD sensor element 61:

$$R_1 = \frac{V_{R1}}{V_{RREF}} (R_{REFNOM}) \quad \text{Equation 2}$$

where:

$R_1$  = resistance of RTD sensor element 61;  
 $V_{R1}$  = voltage drop across the RTD sensor element 61;  
 $V_{RREF}$  = voltage drop across resistance  $R_{REF}$ ; and  
 $R_{REFNOM}$  = nominal resistance of the reference resistance  $R_{REF}$  in Ohms, and/or stored in memory 56.

Microprocessor 52 measures the voltage drop  $V_{R1}$  across RTD sensor element 61 between terminals 2 and 3, and the voltage drop ( $V_{RREF}$ ) across reference resistance  $R_{REF}$  with multiplexer 46. In a four-wire resistance measurement such as the one shown in Figure 2, the voltage drop across the connections to terminals 2 and 3 is largely eliminated, since substantially all of the current  $I_s$  flows between terminals 1 and 4, and has little impact on the accuracy of the measurement. Microprocessor 52 converts the measured resistance  $R_1$  into temperature units with a look-up table or suitable equations stored in memory 30. For example, one such equation is the Callender-Van Dusen equation which is:

$$R(t) = R_0 \left\{ 1 + \alpha \left( t - \delta \left( \frac{t}{100} \right) \left( \frac{t}{100} - 1 \right) - \beta \left( \frac{t}{100} - 1 \right) \left( \frac{t}{100} \right)^3 \right) \right\} \quad \text{Eq. 3}$$

Where:

$R(t)$  = Resistance at temperature  $t$ , in Ohms.

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$R_0$  = Resistance at temperature 0, in Ohms.

$t$  = Temperature, deg C.

$\alpha$ ,  $\delta$ ,  $\beta$  = Calibration constants.

$\beta = 0$  for  $t > 0$  deg C.

5                   However, both stored lookup tables or the  
equation 2 must be properly calibrated for a particular  
RTD temperature sensor. Further, such calibration tends  
to change over time as the alpha ( $\alpha$ ) for the sensor  
drifts. Calibrating an RTD requires an accurate  
10 thermometer reference to obtain a number of correct  
temperature values in order to accurately determine the  
constants  $\alpha$  and  $\delta$ . Equation 3 and transmitter  
calibration are discussed in PRT Handbook Bulletin 1042,  
dated February 1985, published by Rosemount and  
15 incorporated by reference into this application.

The SH index is calculated when microprocessor  
52 actuates switch 138 to couple current source 140 to  
sensor 61.  $P_1$  and  $R_1$  of equation 1 are calculated with  
current  $I_{SH}$  from source 140 flowing through sensor 61.  
20 Microprocessor 52 determines  $P_2$  and  $R_2$  due to current  $I_s$   
from source 45. The SH index is calculated using  
equation 1. If transmitter 40 is completely powered  
from loop 6, the currents  $I_{SH}$  and  $I_s$  are limited to the  
current  $I$  in loop 6, less any current required to  
25 operate circuitry in transmitter 40.

Microprocessor 52 performs diagnostics related  
to operation of transmitter 40 using the SH index. The  
following describes a number of embodiments for  
realizing the diagnostic circuitry in transmitter 40.  
30 Such diagnostics include determining sensor health,  
performing a residual lifetime estimate may be  
representative of an impending sensor failure, or  
performing an autocorrection to the temperature  
measurement.

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Another aspect of the present invention includes the use of the self heating index to correct the temperature measurement to reduce errors due to drift in alpha ( $\alpha$ ) and/or  $R_0$ . As the RTD sensor ages, the constant(s) alpha ( $\alpha$ ) and/or  $R_0$  (given in equation 3) for the sensor, changes thereby causing inaccuracies in the temperature measurements. It has been discovered that there is a substantially linear relationship between the SH index and error in the temperature measurement caused by drift in alpha ( $\alpha$ ) and/or  $R_0$ . The temperature can be corrected using the equation:

$$T_{corrected} = T_{measured} + K(\Delta SHI) \quad \text{Eq. 4}$$

where:

$T_{measured}$  is the measured temperature;

15  $K$  is a constant of proportionality which is a function of the change in the self heating index; and

$T_{corrected}$  is the autocorrected temperature.

The relationship between  $K$  and the change in SHI may be determined experimentally. Determination of  $K$  may be through an equation or, in one preferred embodiment, with a lookup table stored in memory 56 as a function of change in SHI. Similarly, SHI, or change in SHI, can be correlated to alpha ( $\alpha$ ) and  $R_0$ , or changes in these constants. Further, it is within the scope of the present invention to correlate SHI or  $\Delta SHI$  to other constraints in Equation 3.

Figure 3 is a block diagram 150 illustrating the present invention as it relates to autocorrection of the temperature output as a function of the SH index. Diagram 150 shows operations which would typically be performed by microprocessor 52 in Figure 2. At block 152, the previous value of the self heating index ( $SHI_1$ ) is obtained, for example, from memory 56. This value

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may have been stored in memory during manufacture, previously generated by microprocessor 52 or determined and stored when the transmitter was commissioned or even at a preselected time during operation of transmitter

5 40. At block 154 the current value of the SH index ( $SHI_2$ ) is determined by microprocessor 52. If the rate of change,  $m$  is greater than or equal to a maximum allowable rate of change ( $m_{MAX}$ ), decision block 158 provides an alarm output. In general, a value

10 representative of the difference between  $SHI_2$  and  $SHI_1$  is assessed at block 156. A preferred method for this differencing function is to calculate the slope over time of the two SHI values. However, other methods of assessing the amount of difference, some as simple as

15 comparing  $SHI_2$  to a threshold value, can be implemented without block 156. The output may be transmitted, for example, over loop 6 to indicate that the sensor has degraded to such an extent that failure is imminent and replacement is necessary. Other types of

20 diagnostics may also be performed such as those set forth in the parent application U.S. Serial No. 08/744,980, filed November 7, 1996. The value of  $m_{MAX}$  is stored in memory 56 and may be user configurable based upon the accuracy desired for a particular process. The

25 alarming function at block 158 is optional, but preferred to the present invention.

If the alarm condition does not exist, control passes to decision block 160 in which the measured self heating index ( $SHI_2$ ) is compared with the stored self

30 heating index ( $SHI_1$ ). If they are approximately the same, control is passed to block 162 and the temperature is determined. If, on the other hand, there is a

(112) difference between the two values, a new value for the  $ASHI$  in equation 4 is calculated by microprocessor 52 at

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block 164. Further, other more complex curve fitting techniques can be used to correlate SHI with sensor calibration. Control is passed to block 162 and the new value for  $\Delta$ SHI in equation 4 is used in determining  
5 temperature. The new value for  $\Delta$ SHI is stored in memory to replace the previous value.

The various functions set forth in Figure 3 may be performed remotely, in a process control device, in the control room, in a computer located off-site or  
10 in a combination of these locations. Generally, the invention can be practiced in any of a number of places in a process system control system. In particular, the present invention as realized in software and a microprocessor, can reside in a central controller or  
15 even a final control element such as a valve, motor or switch as shown in Figure 1. Furthermore, modern digital protocols such as Fieldbus, Profibus and others allow for the software which practices the present  
20 invention to be communicated between elements in a process control system, and also provide for process variables to be sensed in one transmitter and then sent to the software.

One embodiment of diagnostic circuitry in the present invention uses empirical models or polynomial  
25 curve-fitting which are functions of SH index. For example, a polynomial which is a function of the SH index is used for computing the residual lifetime estimate. The constants and/or the equations may be sent over the two wire loop to transmitter 40. Another  
30 diagnostic circuit is implemented with a multi-layer neural network. Although a number of training algorithms can be used to develop a neural network model for different goals, one embodiment includes the known Backpropagation Network (BPN) to develop neural network

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modules which will capture the nonlinear relationship among a set of input and outputs(s).

Another embodiment of diagnostic circuitry 52 uses a set of if - then rules to reach a conclusion on the status of the temperature sensor RTD 61. The SH index is monitored and its present value is compared to upper and lower boundaries. The upper and lower boundaries are empirically set by testing of many RTD sensors. A decision is made based upon the comparison.

10 In another aspect of the invention, the rate of change (ROC) of the SH index is correlated with life expectancy of sensor 61. The ROC of the SH index is provided to the diagnostic circuitry implemented in microprocessor 52 which provides an output indicative of expected life, including a warning when the expected remaining sensor life has dropped below a minimum value.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.



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WHAT IS CLAIMED IS:

1. A transmitter in a process control system, comprising:

a resistance temperature sensor sensing a process variable and providing a sensor output;

self heating circuitry coupled to the sensor providing a self heating signal related to a self heating index of the sensor;

analog to digital conversion circuitry coupled to the sensor output and the sensor monitoring circuitry and providing a digitized sensor output and a digitized self heating signal;

output circuitry coupled to a process control loop for transmitting a signal related to sensor temperature; and

diagnostic circuitry coupled to the digitized self heating signal responsively providing a diagnostic output related to sensor calibration as a function of the digitized self heating signal.

2. The transmitter of claim 1 including a memory storing a set of expected results related to the self heating signal.

3. The transmitter of claim 1 wherein the diagnostic circuitry comprises a neural network.

4. The transmitter of claim 1 wherein the diagnostic circuitry comprises fuzzy logic.

5. The transmitter of claim 1 wherein the diagnostic circuitry provides a residual lifetime estimate output.

6. The transmitter of claim 5 wherein the diagnostic circuitry determines the residual lifetime



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estimate as a function of rate of change (ROC) of the digitized self heating signal.

7. The transmitter of claim 1 wherein the self heating circuitry includes a current source and voltage measurement circuitry.

8. The transmitter of claim 1 wherein the self heating circuitry determines the SH index as a function of a change in sensor resistance in response to a change in power applied to the sensor.

9. The transmitter of claim 8 wherein the SH index is calculated as  $(R_1 - R_2) / (P_1 - P_2)$ .

10. The transmitter of claim 1 wherein the output circuitry calibrates the sensor temperature signal in response to the diagnostic output.

11. The transmitter of claim 1 wherein the calibration is a function of the self heating signal.

12. The transmitter of claim 1 wherein the diagnostic output is indicative of sensor life expectancy.

13. A method for diagnosing a resistance based temperature sensor in a process control transmitter, comprising:

sensing and digitizing resistance of the sensor to provide a digitized sensor output;

obtaining a self heating index (SHI) for the sensor;

providing a diagnostic output as a function of the SHI.

14. The method of claim 13 wherein obtaining the SHI comprises measuring change in sensor resistance in response to a change in power applied to the sensor.



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15. The method of claim 14 wherein the self heating index is calculated as  $(R_1 - R_2) / (P_1 - P_2)$ .

16. The method of claim 13 including estimating residual life of the sensor based upon a rate of change of the SHI.

17. The method of claim 13 wherein obtaining the SHI includes sequentially injecting at least two different current levels into the sensor and measuring the resultant voltage drop across the sensor.

18. The method of claim 13 including determining sensor life expectancy as a function of the diagnostic output.

19. The method of claim 13 including determining temperature of the sensor as a function of the sensor output and the SHI.

20. A temperature transmitter for use in a process control system, comprising:

I/O circuitry adapted to coupled to a process control loop;

a resistance based temperature sensor;

a current source coupled to the sensor to inject a current into the sensor;

voltage measurement circuitry coupled to the sensor providing an output related to voltage drop across the sensor; and

diagnostic circuitry providing a self heating (SH) index output as a function of injected current and the voltage drop across the sensor.

21. The transmitter of claim 20 wherein the diagnostic circuitry provides a life expectancy output as a function of the SH index.

22. The transmitter of claim 20 including temperature measurement circuitry providing an output



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related to sensor temperature as a function of sensor resistance and the SH index.

23. The transmitter of claim 20 wherein the SH index is determined as a function of a change in sensor resistance in response to a change in power applied to the sensor.

24. The transmitter of claim 21 wherein the SH index is calculated as  $(R_1 - R_2) / (P_1 - P_2)$ .

25. A temperature transmitter for use in a process control system, comprising:

- a resistance temperature sensor sensing a process variable and providing a sensor output;

- self heating circuitry coupled to the sensor providing a self heating signal related to a self heating index of the sensor;

- analog to digital conversion circuitry coupled to the sensor output and the sensor monitoring circuitry and providing a digitized sensor output and a digitized self heating signal;

- measurement circuitry calculating a measurement temperature of the temperature sensor as a function of the digitized sensor output and the digitized self heating signal; and

- output circuitry coupled to the process control loop for transmitting the measured temperature on the loop.

26. The temperature transmitter of claim 25 wherein a constant  $R_0$  of the temperature sensor changer as a function of change in the self heating signal.



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27. The temperature transmitter of claim 25 wherein a constant alpha ( $\alpha$ ) of the temperature sensor changer as a function of change in the self heating signal.

28. The temperature transmitter of claim 25 wherein the measured temperature is a function of the sensor signal times a constant K.

29. The temperature transmitter of claim 28 wherein the measured temperature is linearly related to K, where K is a function of the self heating index.

30. The temperature transmitter of claim 28 including a lookup table stored in a memory, the lookup table providing K as a function of the self heating signal.

31. The temperature transmitter of claim 25 including diagnostic circuitry coupled to the digitized self heating signal responsively providing a diagnostic output related to sensor calibration as a function of the digitized self heating signal.

32. The temperature transmitter of claim 25 including:

- a current source coupled to the sensor to inject a current into the sensor;
- voltage measurement circuitry coupled to the sensor providing an output related to voltage drop across the sensor; and
- diagnostic circuitry providing a self heating (SH) index output as a function of injected current and the voltage drop across the sensor.